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Structural analysis of a small area in the northeast border zone of the Idaho batholith Idaho

Brian G. White
The University of Montana

STRUCTURAL ANALYSIS OF A SMALL AREA IN THE NORTHEAST

BORDER ZONE OF THE IDAHO BATHOLITH, IDAHO

by

Brian G. White

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Approved by:

Donald W. Hyndman
Chairman, Board of Examiners

John M. Stewart
Dean, Graduate School

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ABSTRACT

A detailed structural analysis of small scale deformational structures was undertaken in a small area of high metamorphic grade northeast of the Idaho Batholith, in the Brushy Fork Creek area of northeastern Idaho. The investigation was confined to feldspathic quartzite, Ravalli Group rocks of the late Precambrian Belt Supergroup. Orientations of mesoscopic structures were recorded with Brunton compass and plotted on the lower hemisphere of an equal-area (Schmidt) stereonet. Those structures examined include deformed bedding and subparallel schistosity, mesoscopic folds and crenulations and their axial surfaces, and striations.

Three dominant fold events are indicated: 1) An early deformation, accompanied by high-grade regional metamorphism, produced large scale isoclinal, recumbent folds, resulting in schistosity largely parallel to bedding. 2) A second major fold event bent schistosity and produced large, recumbent, dominantly flexural-slip folds with northwest-trending axes. One of these folds was investigated in detail and its core was found to be characterized by abundant folded pegmatites, ptygmatic

folds, small, tight folds, crinkle lineations, and a generally profound structural complexity. 3) A final fold event important in the Brushy Fork area folded early structures about an axis plunging steeply to the southeast. This fold event is probably related to strike-slip faulting in the region.

Geometry of the northwest-trending fold event was made evident by stereographic rotation of bedding and axial planes about the steeply plunging, late axis. Abundant, dominantly bedding plane striations may be indicative of final pushing in a N 70° W-S 70° E orientation.

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INTRODUCTION

Location and Accessibility

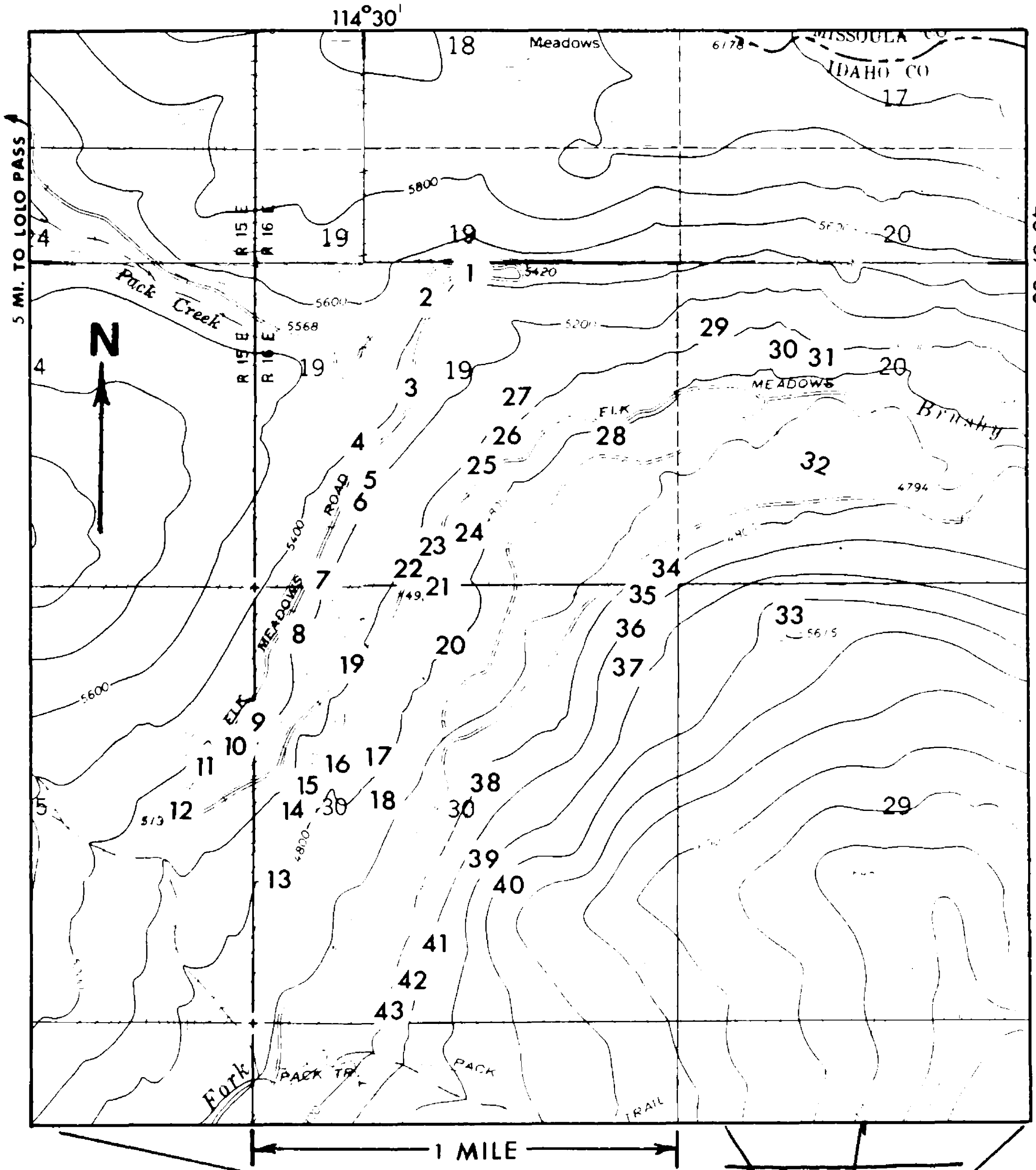
The area investigated covers approximately two square miles along both sides of Brushy Fork Creek, in northeastern Idaho (Fig. 1). The area lies about five miles east of Lolo Pass, and thirty miles southwest of Missoula, Montana.

Access to the Brushy Fork project area is gained on the Elk Meadows road, heading east from Lolo Pass. Heavy snow makes access impossible from December through May, but during the summer months the road is accessible with ordinary highway vehicles.

Physiography, Vegetation, and Climate

Brushy Fork Creek in the project area lies in a steep-sided glacial valley, with elevations ranging from 4600 to 5600 feet (fig. 2). Outcrops commonly occur as isolated, glacially rounded knobs.

The northwest-facing side of the valley of Brushy Fork Creek is thickly timbered with spruce and fir, and underbrush is extremely dense. Larch and ponderosa pine are predominant on the southeast-facing side of the valley,



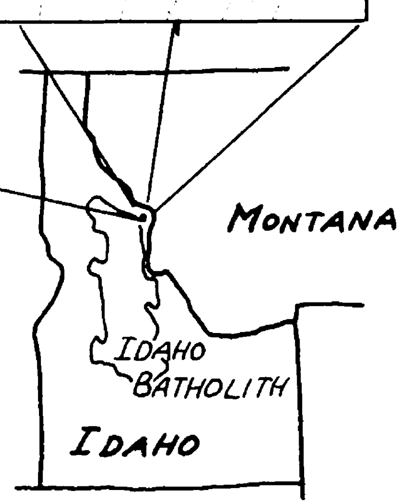


Fig. 1.--Index map showing location of the project area. The outline of the Idaho Batholith and the location of stations are also indicated.

Fig. 2.--View of Brushy Fork Creek valley. Looking east from upper switchback in Elk Meadows Road in the northern part of the project area.

and there is considerable less underbrush.

Snow depths in the area probably reach six to eight feet or more, based on depths at Lolo Pass, five miles to the west. During the spring, and until mid-June, there are frequent rain showers. Summer weather is generally fair, with daytime temperatures reaching the 70's, falling at night to the 40's or low 50's.

Previous Work

The general geology of the immediate region has been reported by Nold (1968). He recognized two dominant fold trends, both subsequent to isoclinal folding during regional metamorphism which caused schistosity to develop nearly everywhere parallel to bedding. The folds which he believes to be the earliest of the two plunge gently to the southwest. The second fold trend is oriented in a northwest-southeast direction. The combined effect of the two fold trends is to produce large scale interferring antiforms and synforms.

The only other structural analysis in the region, based on detailed geometry of small scale structures, is that undertaken by Chase (1968). He made a detailed analysis of several outcrops in the upper Bass and Kootenai Creeks area, about ten miles east of the Brushy Fork area. Chase found evidence for two flexural slip deformations, which are superposed upon schistosity that is parallel to bedding wherever lithologic layering is apparent. Interpretation of the flexural-slip deformations was based on stereographic treatment of two generations of mesoscopic folds, the first of which plotted as small-circle girdles with a common axis, and the second of which plotted as a great circle girdle passing through that axis. Unrolling of the second flexural-slip folds resulted in a great circle pattern of poles to bedding of the earlier folds, with their β axis trending S 45° W and plunging 65°. The second flexural-slip deformation has a N 43° W striking axial plane that dips steeply southwestward. Chase found that the same structural geometry is present on a macroscopic scale as well, over quite a large area of the northern Bitterroot Range. He further suggests a later, large scale warping about a very steeply plunging axis.

All other structural work in the region has been of a gross nature, interpretations being made primarily from geologic maps. Just northwest of the Idaho Batholith, Hietanen (1961) has described four major sets of fold axes, three of which occur in many individual outcrops. These include isoclinal folds with eastward-trending axes, folds on northeast-trending axes which are isoclinal and overturned, northwestward-trending axes.

West of the Idaho Batholith Morrison and Greenwood (1967) report fold events in the following sequence: 1) West-northwest isoclinal folds with concomitant axial plane schistosity, 2) major northwest trending folds with insipient to good axial plane schistosity, 3) northeast trending folds with local axial plane schistosity, and 4) north-south subisoclinal to relatively open folds and kink folds which locally overprint earlier structures. Morrison and Greenwood believe the earliest of these events to be Precambrian.

Reid, et al. (1967) report essentially the same sequence and trends in the St. Joe area, north of the Idaho Batholith. Here they believe the earliest two fold events to be Precambrian.

A number of workers in the vicinity of the northern Bitterroot Range (Chase, 1961; Anderson, 1959; Langton, 1935; Hall, 1968; and Wehrenberg, 1967) have indicated two major fold events for this area. The resultant folds trend either northwest, or north-south to north-northeast. However, these workers are divided on which of the two events was earliest.

Present Study

This study was originally suggested by John Nold, who recognized the Brushy Fork Creek area as being one of the most structurally complex areas which he encountered in a large mapping project centered on Lolo Pass (Nold, 1968).

The objective of this investigation is to ascertain the number, sequence, style, and geometry of the deformations present. The project was undertaken with the hope that information gathered in a detailed investigation of a critical small area would help clarify structure on a more regional scale. Due to the great similarity of lithology throughout the area and lack of marker beds, detailed structural analysis is the only means possible for clarifying the structural history.

Acknowledgements

The author wishes to express thanks to Dr. D. W. Hyndman, who advised throughout the project, and who provided often-needed encouragement. Special thanks are due to John L. Nold, who originally suggested the project and directed the initial efforts.

The author benefited as well from discussions with Ronald B. Chase, Frank W. Hall, and Dr. G. W. Crosby.

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REGIONAL GEOLOGY

Pre-Tertiary sedimentary rocks in the immediate region are all of the Late Precambrian Belt Supergroup. These rocks are subdivided into several groups, but each group itself is thick and monotonously uniform in appearance throughout.

The study area is located on the northeast border of the Idaho Batholith, in rocks which Nold (1968) has referred to as plagioclase zone (An greater than 15) metamorphic grade. The Idaho Batholith cuts the regional metamorphic isograds, although on a gross scale, metamorphic grade decreases going away from the batholith.

Nold has examined regional metamorphic rocks on the northern and western sides of the batholith and reports (1968) that they are very similar to those along the northeast border. These high-grade metamorphic equivalents of Supergroup rocks have been described in numerous papers, e.g. Hietanen (1960, 1962, 1963a, 1963b, 1963c, 1968, 1969), Reid (1959), Reid, et al. (1967), and Morrison and Greenwood (1967).

A definite stratigraphic progression to younger

Beltian formations in outcrop going away from the Idaho Batholith takes place over a large area to the north. Pronounced decrease in metamorphic grade also occurs to the north across the steep, east-west trending Lolo Fault, and again farther northeast across a similar fault in an area mapped by Hall (1968). The change in metamorphic grade across the Lolo Fault is most pronounced in the east, and fades out as the fault decreases in dip and begins to swing northward and die out to the west (Hall, personal communication, 1968).

A dramatic decrease in metamorphic grade also takes place eastward across the Bitterroot Valley to the Sapphire Range, only a few miles away. Beltian rocks there are biotite grade or lower.

Abundant north to northeast-trending, sub-vertical faults occur over several thousand square miles within and adjacent to the northern portion of the Idaho Batholith (Nold, 1968).

METHODS AND FIELD PROCEDURE

All structure orientations were measured with Brunton compass and plotted on the lower hemisphere of a standard, 20 cm, equal-area (Schmidt) stereonet. Additional field tools included rock hammer and cold chisel, for exposing fresh surfaces. Also useful was a felt-tipped pen, used to mark lineations for easier measuring, and a small level, to aid in determining strikes on surfaces which were not well enough exposed to accurately apply a Brunton compass to.

Due to extreme structural inhomogeneity, it was found useful to carry the stereonet in the field at all times, pausing frequently to plot readings for examination.

For the purpose of this investigation, a "station" is equivalent to an outcrop, or to some convenient, arbitrary small area of outcrop. A total of 43 stations was established. Gross homogeneity is characteristic of each station; i.e., each station has diffuse great circle and/or point maxima distributions, which may or may not be identical to patterns of other nearby stations. "Ideal homogeneity at each station commonly exists only on a very small scale, on the order of several feet, or even inches. On the basis of gross homogeneity, a number of sub-domains are distinguished (Fig. 3). The number of individual lineation or foliation measurements at each station generally ranges from several dozen to around a hundred.

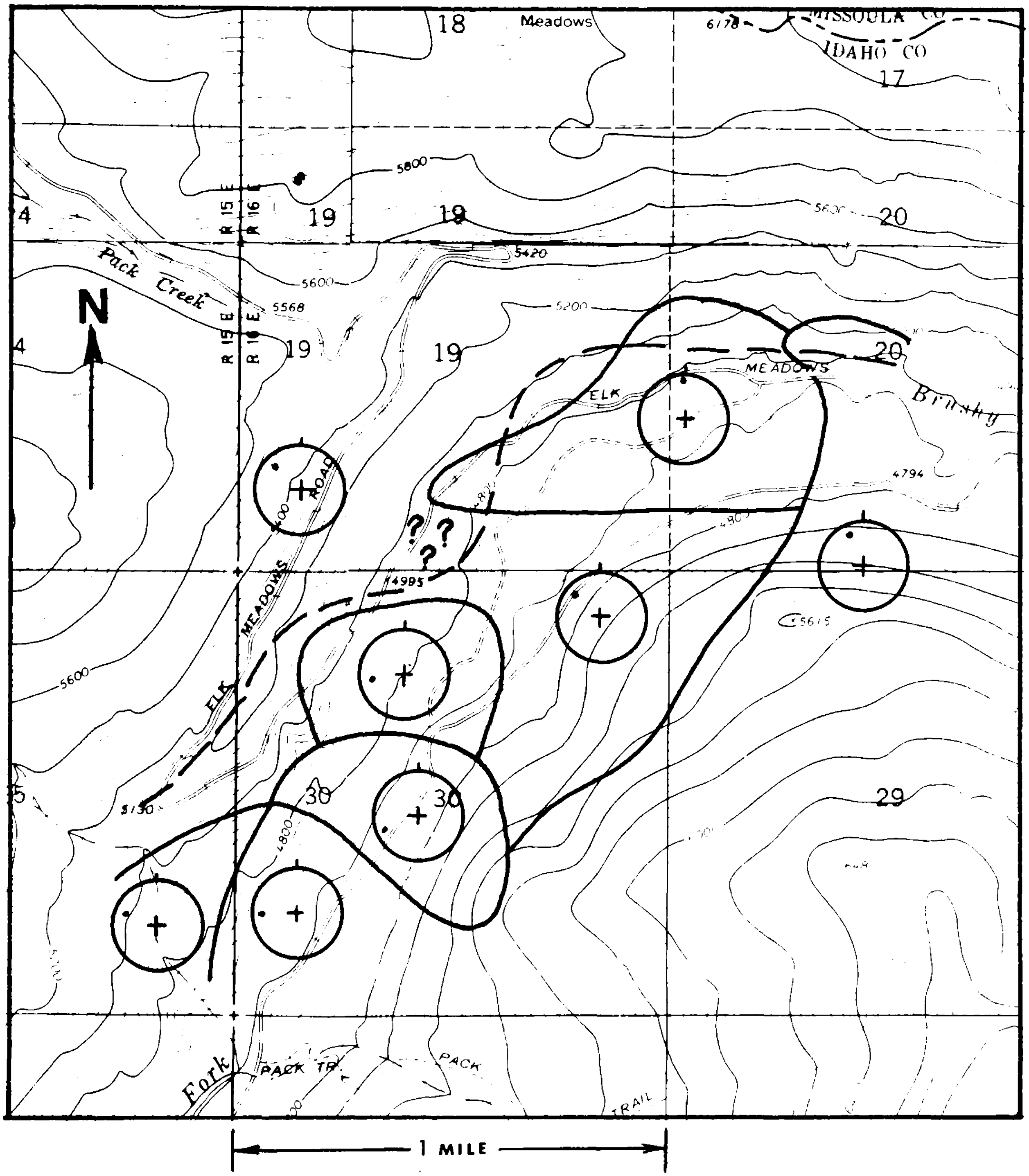

Fig. 3.--Fold trend sub-domain map. Stereograms represent average B fold trends characteristic of each sub-domain. Broken line separates major northwest and southeast domains, distinguished by degree of deformation.

DESCRIPTION OF STRUCTURAL ELEMENTS

Measurable structural elements fell into three categories: 1) bedding and schistosity; 2) mesoscopic fold axes and crenulations and their axial surfaces; and 3) striations.

Schistosity and Bedding

The meta-sedimentary rocks in the project area belong to the Ravalli Group (Nold, 1968). They are feldspathic quartzites that contain thin micaceous laminations. The rocks tend to separate along the thicker laminations, occasionally exposing virtually a single bedding surface over an area of several hundred square feet (Fig. 4).

That this surface in these fairly high grade metamorphic is truly bedding is evidenced by the continuity of the parallel laminations, and the presence of obvious crossbeds at two stations (stations 35 and 36). Where observed, the crossbeds indicate that bedding is upright locally, if not for nearly all of the project area.

Pronounced schistosity of micas is found throughout the project area in the pelitic layers. Schistosity is

Fig. 4.--Single bedding surface exposed over a large area due to easy separation of rocks along highly micaceous layers (station 17). Linear features are B mesoscopic folds. Rocks in this photograph are untypically homogeneous.

nearly every case parallel to bedding. It is especially prominent in the southeast half of the area, as well as in thick pelitic layers in the north and northwest part (e.g. station 1). Schistosity is everywhere bent by later folding--very severely in the southeast half, but only gently and on a much larger scale in the northwest. Only at one station (station 5) was schistosity observed to lie at an abvious angle to bedding. Here the angle between bedding and schistosity is observed to change from 0° to 90° across a small fold. Inasmuch as schistosity is bent around all other folds, it is interpreted that schistosity is related to early isoclinal folding that accompanied regional metamorphism. The probable style of this early folding is illustrated schematically in figure 5. The orientation of these folds is unknown.

Mesoscopic Folds and Crenulations

This category of structural elements includes bedding and schistosity that is folded on such a small scale that the orientation of axes can be measured as a lineation.

Tight mesoscopic folds in the area which bend the pre-existing schistosity are dominently flexural-flow, in the terminology of Donath and Parker (1963) (Fig. 6).

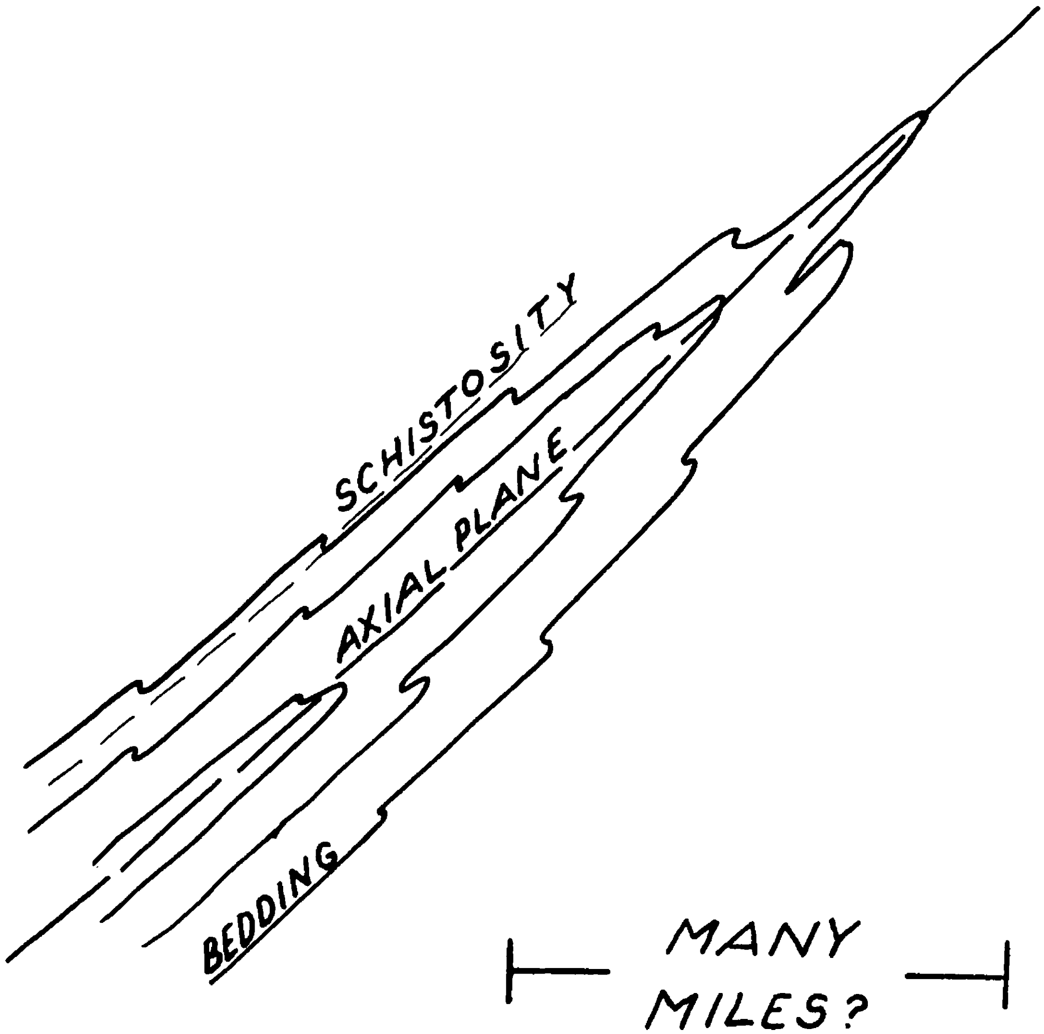

Fig. 5.--Schematic representation of presumed style of early isoclinal folding which accompanied regional metamorphism.

a.

b.

Fig. 6.--Photographs illustrating mesoscopic flexural-flow folds (station 34).

Thickening in the crest is commonly noted in tight folds, even in the more competent layers. More gently folded layers frequently exhibit the geometry of flexural-slip folding (Fig. 7). Although bedding may be severely disrupted, well defined mesoscopic folds and crenulations are not extremely abundant.

Nold (1968) noted that in this region micas occasionally have undergone reorientation in the cores of small, tight folds, transposing into secondary axial plane schistosity. Insipient secondary schistosity of this sort was rarely observed in the present project area. Axial planes of small folds were recorded, however, whenever possible.

Crenulations, or "crinkle lineations" are found only in highly micaceous layers. In form, they tend to be flexural slip, although infrequently the crinkles are very sharply crested and straight flanked, or chevron in style.

Striations

Bedding plane striations, or slickensides, are fairly abundant. However, they are often very difficult to see, especially in the shade. A convenient means found to discern striations was to break off a piece of rock and examine it in the sunlight. If striations

a. b.

Fig. 7.--Photographs illustrating flexural-slip style of gently folded layers (a--station 34; b--station 17).

were found, the lineation was then marked with a felt-tipped pen, and the specimen replaced in its original position on the outcrop for the orientation measurement.

The most pronounced striations tend to lie in immediate proximity to small, tight, isolated fold crests, often on short shear surfaces which transect bedding in the immediate vicinity of the fold crest. In the northwest part of the area, where deformation appears mildest, striations are rarely observed.

Bedding commonly separates most easily along surfaces that show striations. Such surfaces are also often observed to have upon them a rusty stain, a relationship consistent enough so that presence of rusty stain on a freshly separated bedding surface likely indicates that striations are present.

MEASUREMENT AND INTERPRETATION

Introduction

The project area is divisible into two distinctively different areas, based on degree of deformation. All outcrops southeast of a line that approximately follows the lowest portion of the Elk Meadows Road through the area (see Fig. 3, p. 12) are severely deformed. These rocks contain abundant mesoscopic folds and crenulations, and strongly deformed bedding and schistosity. Discontinuous pegmatite veins and ptygmatically folded veinlets are common. In the words of Nold (personal communication), the rocks frequently have the appearance of having been "stirred with a spoon."

In sharp contrast, the area lying primarily northwest of the lower portion of the Elk Meadows Road is only gently folded, and on a much larger scale. Mesoscopic folds and crenulations, pegmatite veins, and localized bedding disruption of any sort related to post-isoclinal folding, are essentially absent.

These two areas will henceforth be referred to respectively as the "southeast domain" and the "northwest domain" of the project area.

In the southeast domain, poles to bedding at each station tend to plot as more or less diffuse portions of great circle girdles, whereas in the northwest domain, poles to bedding plot as approximate point maximum distributions at each station.

In the southeast domain mesoscopic fold axes and crenulations plot as smeared-out point maxima producing partial girdles. Plots of these lineations at each station also correspond closely to the β-axis of the diffuse bedding girdle for that station. Examination on a much smaller scale of individual outcrops which produce bedding girdles (Fig. 8), indicates that much of the diffusion of plotted bedding and axial directions is due to an apparent rotation about a steeply plunging axis.

Distinguishable Fold Sets

Axes of mesoscopic folds and crenulations which bend the schistosity belong to three separate, superimposed sets. They shall be referred to respectively as B, B', and B''. B is especially prominent, and is apparent everywhere throughout the southeast domain, where it is distinguished by axes which are nearly horizontal, or plunging at most about 20°.

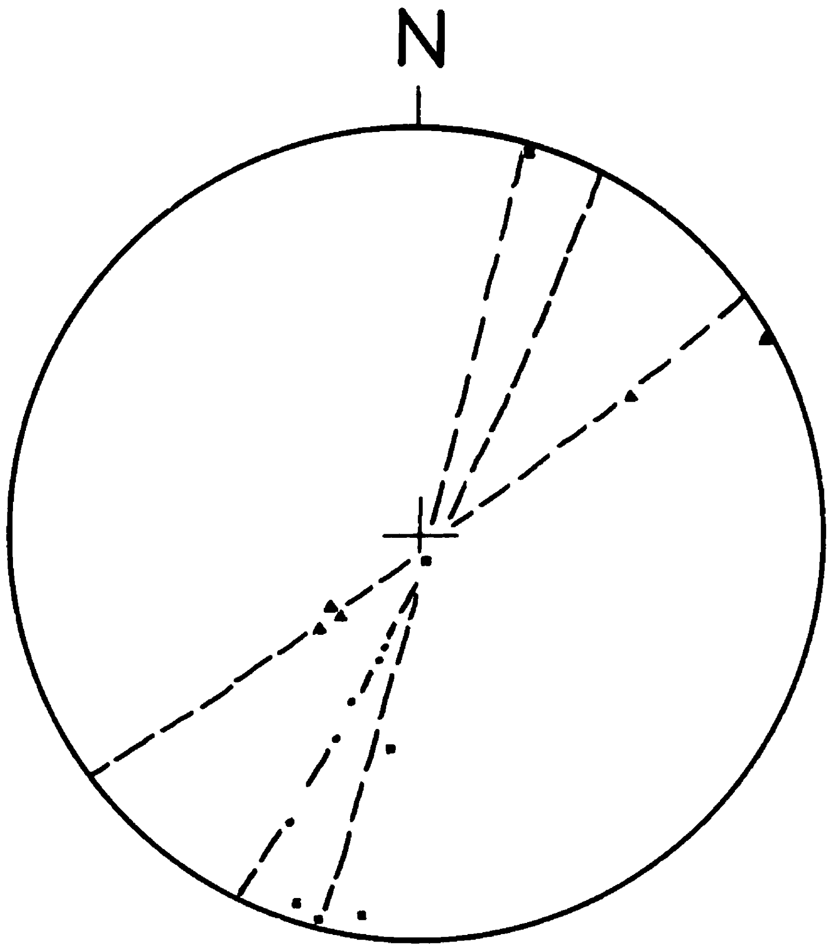

Fig. 8.--Stereogram illustrating apparent rotation of earlier folds about an approximately vertical axis (at station 35). Girdles are bedding from three different, homogeneous, small folds in close proximity to each other. The same type of pattern was frequently observed at other stations.

B' mesoscopic folds and crenulations are found on steeply-dipping bedding surfaces in the southeast domain (e.g., station 17), but are only rarely evident. Where observed, they are of identical style to the before-mentioned set, but plunge at a slightly steeper angle. B and B' are observed to intersect in outcrop. These structures may be either larger or smaller than mesoscopic folds and crenulations of the other fold sets.

B'' folds are distinct in outcrop at only three stations, where bedding is near-vertical. At two of these stations, 16 and 19, B'' is developed as steeply-plunging, concentrically folded broad warps, three to eight feet across. At the third station, 13, this fold set is represented by a steeply-plunging, tight fold about five inches across, the orientation of which, however, was not possible to measure. At station 16, the steeply-plunging axis has crenulations associated with it.

Local fold orientations determined by averages of axes of B mesoscopic folds and crenulations, and β-axes for all stations where this data is available, plot on stereonet as a diffuse great circle girdle (Fig. 9). The pole to this girdle is oriented 70° to the east-southeast, and is interpreted as being associated with the steeply-plunging folds found in outcrop.

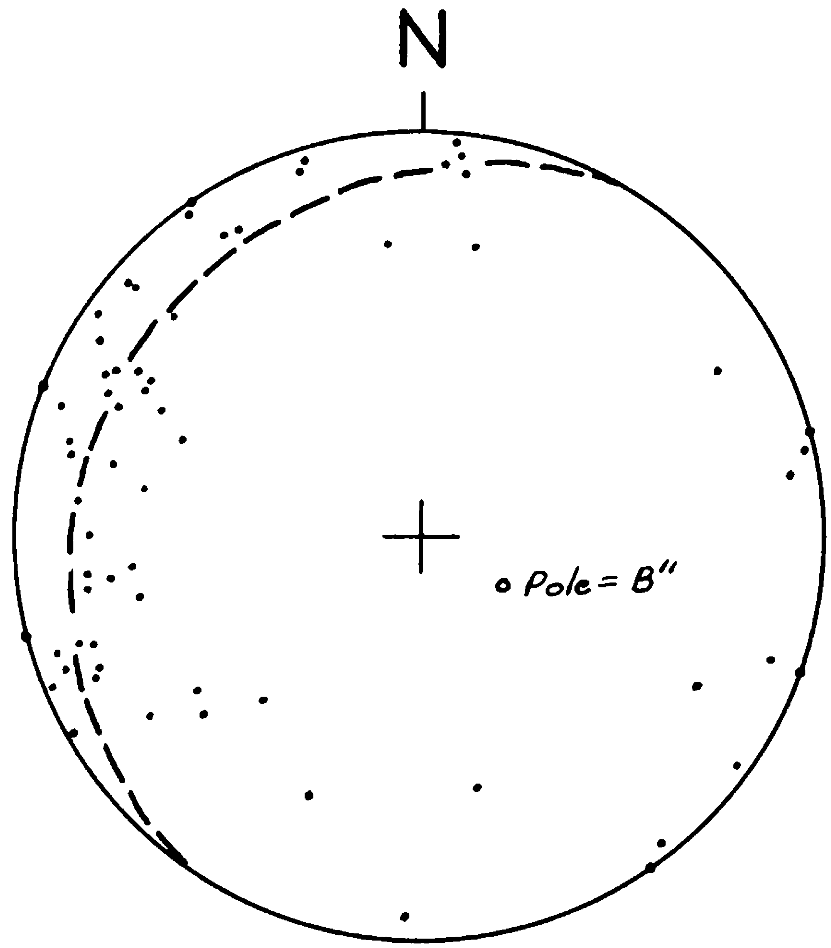

Fig. 9.--Stereographic plot of local B fold orientations determined by averages of axes of mesoscopic folds and crenulations, and β-axes for all stations exhibiting bedding girdles.

Unrolling About Steeply-Plunging Axis

The steeply-plunging B'' folds fail to be pervasive throughout any part of the project area, in direct contrast to the dominent B folds within the southeast domain. In the northwest domain folds that may be related to B'' are not observed at all. This strongly suggests that B'' folding occurred later than B, the dominant folding. Inasmuch as the stress field for a near-vertical fold axis in an area of steeply dipping beds is the same as that for strike-slip faulting (i.e., intermediate principal stress vertical, such folding may well be related to strike-slip movement on the many high-angle faults observed in the region.

The observation of flexural-slip, or concentric style of the B'' folds at several stations suggests that this folding may also be flexural-slip on larger scales as well. For such folding, the great-circle pattern of B fold directions (Fig. 9, p. 25), rather than a small-circle pattern which might be expected from second generation flexural-slip deformation, is a simple consequence of the two axes having the unique relationship of mutual perpendicularity.

Since flexural-slip is considered to be the mechanism of the steep-axis folding, it is possible to unroll earlier structures which were refolded about the steep axis.

Individual fabrics at each station form slightly dispersed stereonet groupings, due in large part to rotation on a small scale about the steep axis. However, useful data are obtained by averaging these dispersed groupings. All average orientations were determined by visual estimation. Except for the bedding girdle of one station which encompasses 180°, it was deemed reasonable to take the center of point density for each bedding partial girdle or point maxima distribution as representative of the average bedding orientation for that station. A stereographic plot of averaged bedding pole orientations for all stations is shown in figure 10. Averaged bedding orientations as they appear in map view are shown in figure 11. Each average represents a minimum of about a dozen bedding poles for several stations with point maxima distributions, and for the most part many more, especially for well-folded stations.

The stereographic plot of poles to averaged bedding (Fig. 10) shows orientations of the northwest domain concentrated in a girdle, while the bedding orientations of the southeast domain are scattered somewhat randomly. Bedding orientations at stations throughout

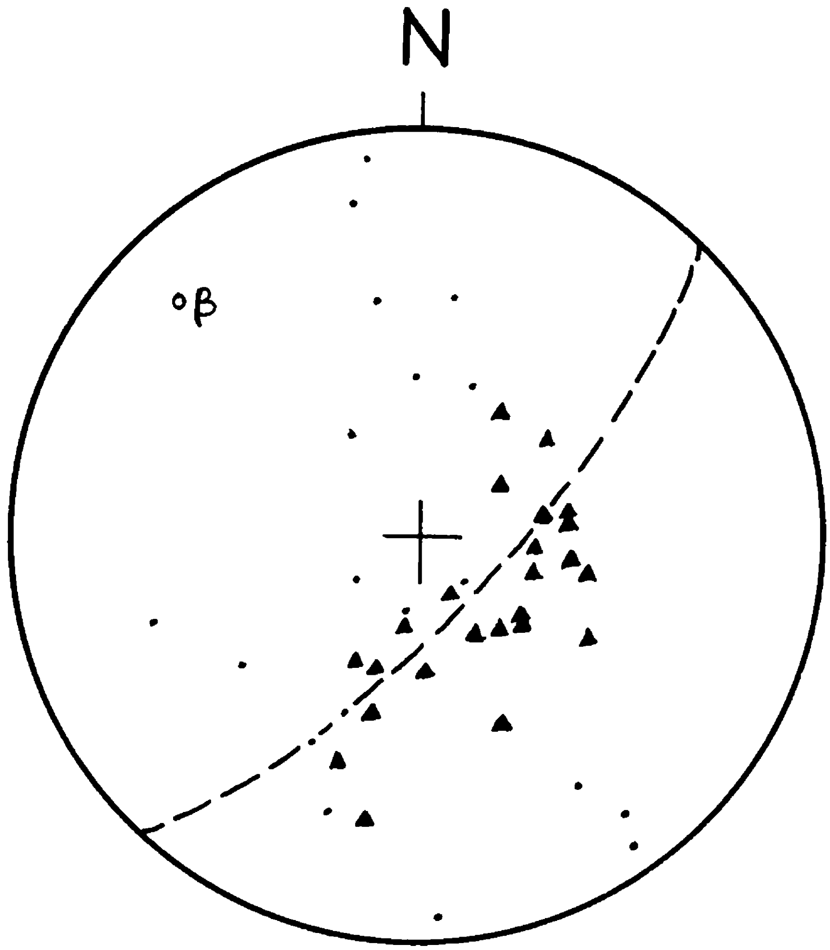

Fig. 10.--Stereographic plot of averaged bedding orientations for all stations. Dots are from southeast domain. Triangles show girdle pattern of northwest domain.

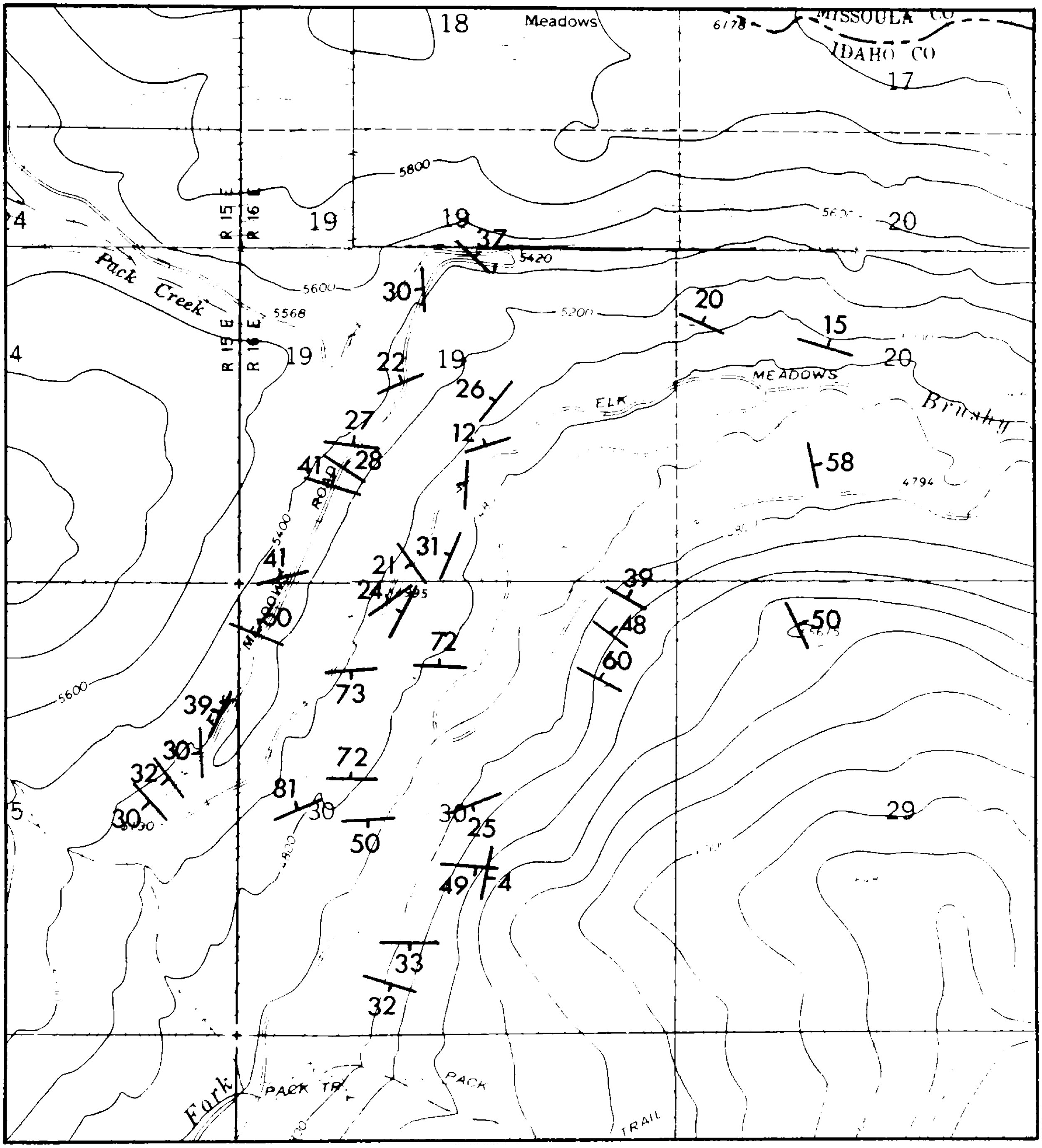

Fig. 11.--Map of averaged bedding orientations.

the northwest domain appear to represent a portion of a great circle girdle. In addition, the β-axis of this girdle lies on the great-circle girdle formed by mesoscopic fold axes and crenulations found throughout the southeast domain (Fig. 12). The northwest domain is, then, a large, structurally homogeneous domain, folded around an axis plunging gently northwest--the same fold event which dominates in the southeast domain, but folded on a much larger scale.

The northwest domain occupies about half of the project area. Since it is the largest single homogeneous domain in the project area (Fig. 3, p. 12), it is logical to rotate all other structural fabric into the frame of reference of the northwest domain.

A convenient means of performing such an operation is to rotate each structural fabric around the B'' axis (Fig. 9, p. 25) through an arc equal to the difference in angle between an associated B fold axis direction and β of the northwest domain. The operation is facilitated through the use of an inclined axis stereonet. Bedding rotation for each station is done by rotating the averaged bedding orientation, associated with an averaged mesoscopic fold and crenulation orientation for that station. Axial surfaces of small folds are rotated back around B'' through

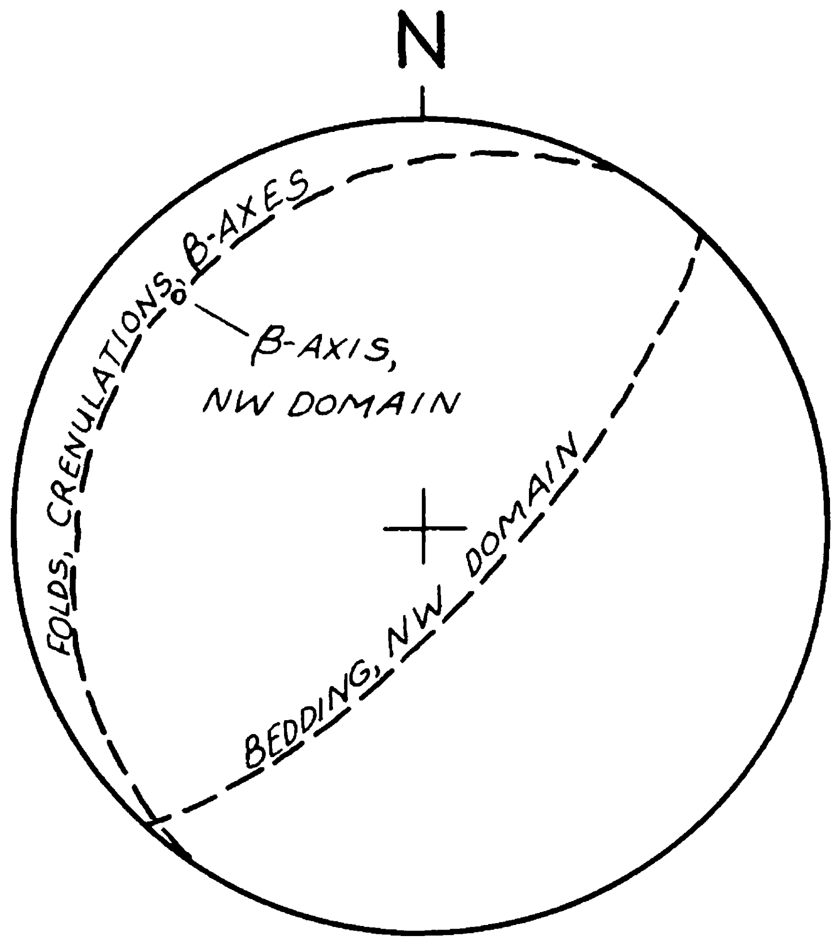

Fig. 12.--Stereographic plot demonstrating position of β-axis of the northwest domain on the girdle of B directions of the southeast domain. (See Figs. 9 and 10, p. 25 and 28.

an arc determined by the difference between their respective fold axes and β of the northwest domain.

Subsequent rotation of averaged bedding results in a great circle distribution with its β plunging 16° N 43° W (Fig. 13). This closely approximates of the northwest domain (17° n 45° W). It is, of course, apparent that unrolling each individual bedding orientation measurement from each station would result in the same pattern. However, the pattern would necessarily be more spread out, since folding about the steep axis is present on a small scale as well as macroscopically.

The great circle rotated-bedding girdle suggests that the northwest-trending folds developed in layers that were essentially planar as a consequence of the early isoclinal fold event (see Fig. 5, p. 16), and that no significant interceding deformation occurred.

Folds upon which axial surfaces can be measured are not abundant. Those few measured form a large, very dispersed distribution on the stereonet (Fig. 14). No pattern of any sort is apparent. The pattern of axial planes which have been rotated back around the steep axis, as above, (Fig. 15) is also somewhat dispersed. The pattern is, however, suggestive of the great-circle girdle formed by the rotated bedding, as it theoretically should be.

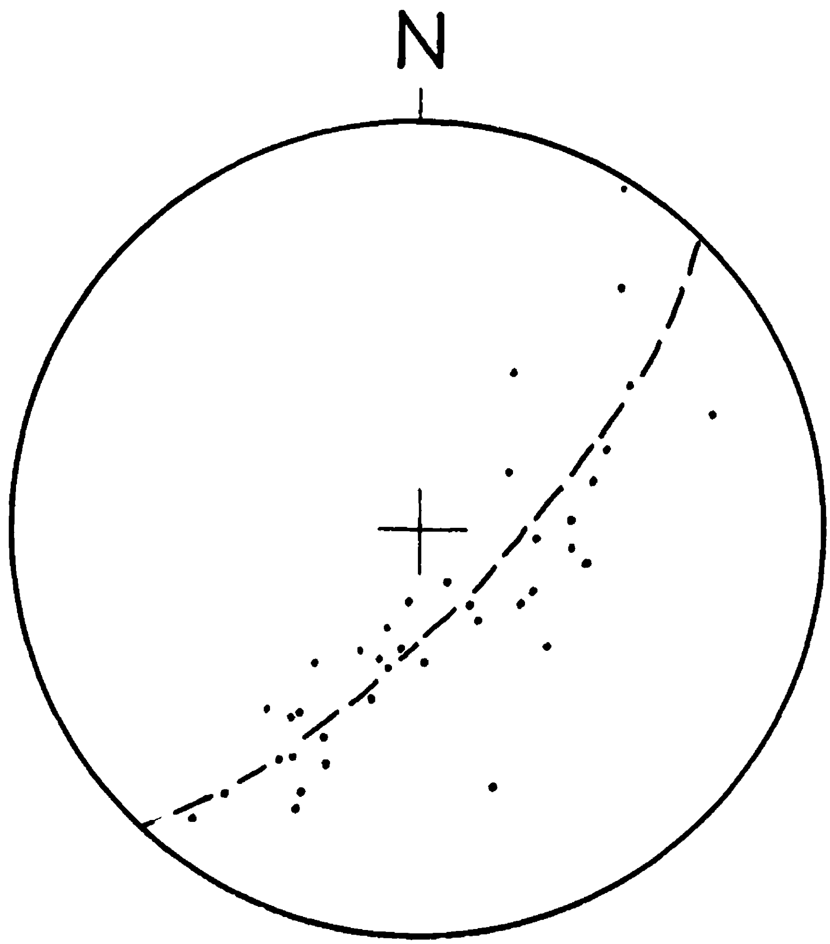

Fig. 13.--Stereographic plot demonstrating great circle distribution for unrolled bedding. (Compare Fig. 10, p. 28.)

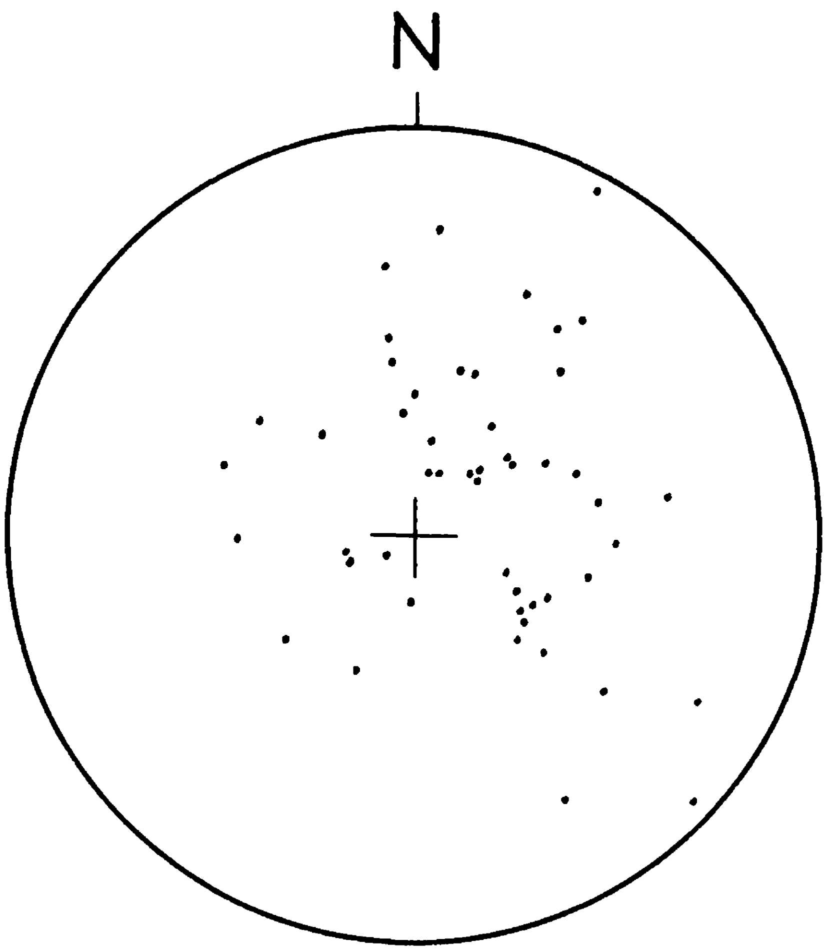

Fig. 14.--Stereographic plot of axial surfaces of B mesoscopic folds.

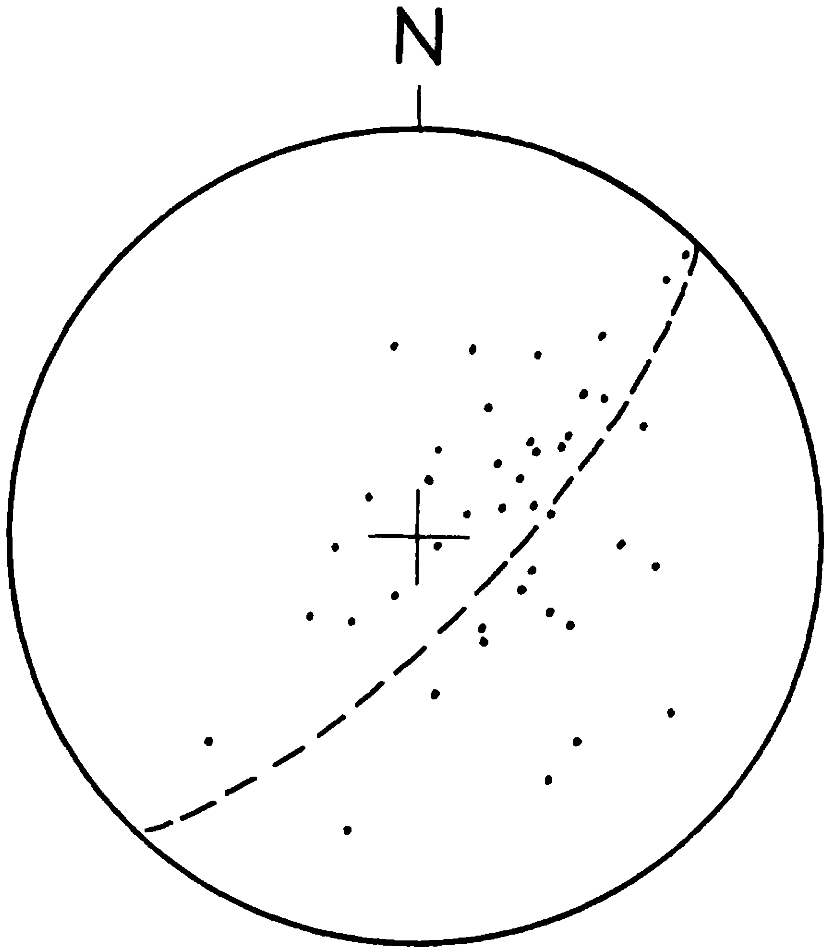

Fig. 15.--Stereographic plot of unrolled axial surfaces of B mesoscopic folds, and great circle girdle of unrolled bedding (see Fig. 13, p. 33).

The center of point density indicates the northwest folds to be overturned 70 to 80° to the northeast.

Attempts were also made to rotate back the remaining, infrequently-seen fold trend (Fig. 16) using similar techniques. Average orientations of this fold trend were used for each station. Although too few field measurements were obtainable for this operation to be statistically sound, the resultant pattern (Fig. 17) appears to be a point distribution indicative of a northwest fold direction that plunges somewhat more steeply than the dominant northwest B folding. Since B' mesoscopic folds and crenulations are identical in style to the B folds, and since they are found only in the highly deformed southeast domain, it seems likely that they represent a minor phase, probably late, of the dominant northwest deformation.

Striations

Two different, dominantly bedding plane shear-striation sets are occasionally observed to intersect at nearly right angles. One set is only rarely visible, but appears to lie in a steep northeast-trending great circle girdle (Fig. 18). It is differentiated from the other set only where the two are observed to intersect. Only a few striations of this set were distinguishable.

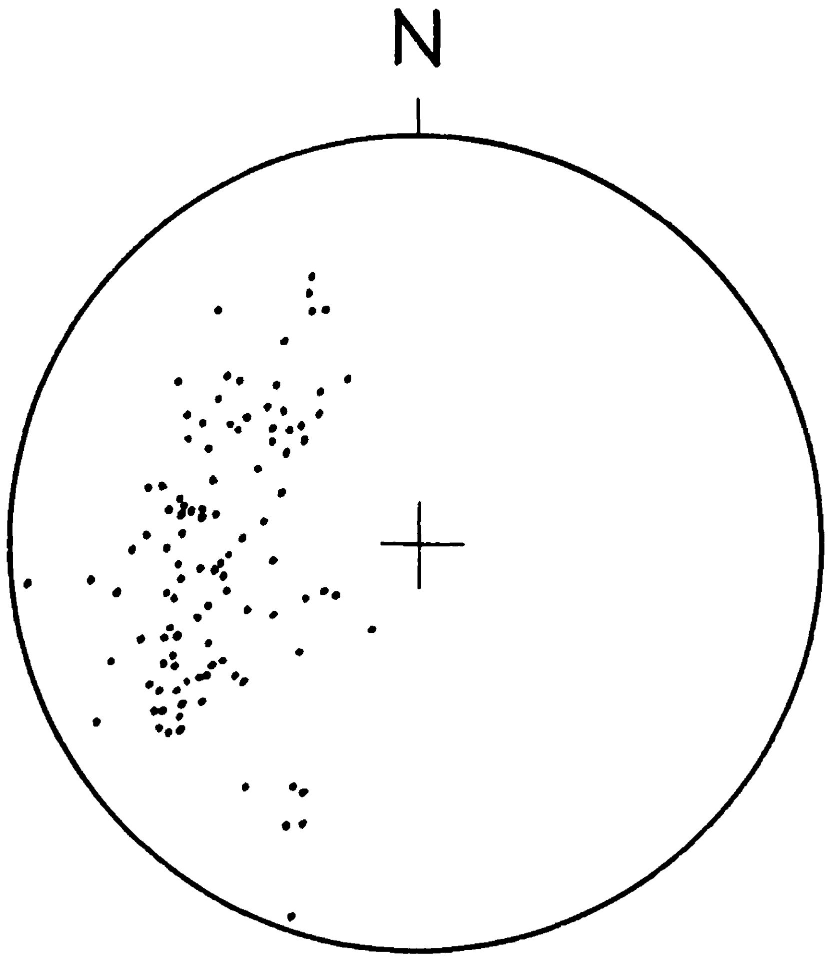

Fig. 16.--Stereographic plot of B' mesoscopic fold axes and crenulation lineations (individual measurements, not averaged).

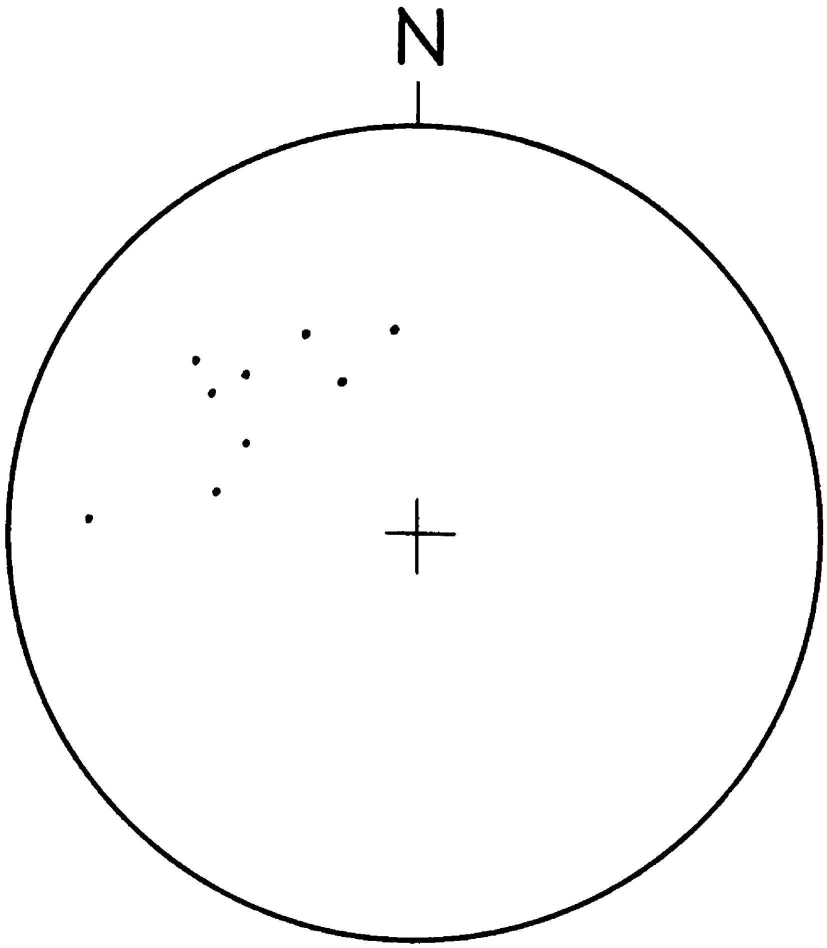

Fig. 17.--Stereographic plot of unrolled averaged axis orientations of B' mesoscopic folds and crenulations.

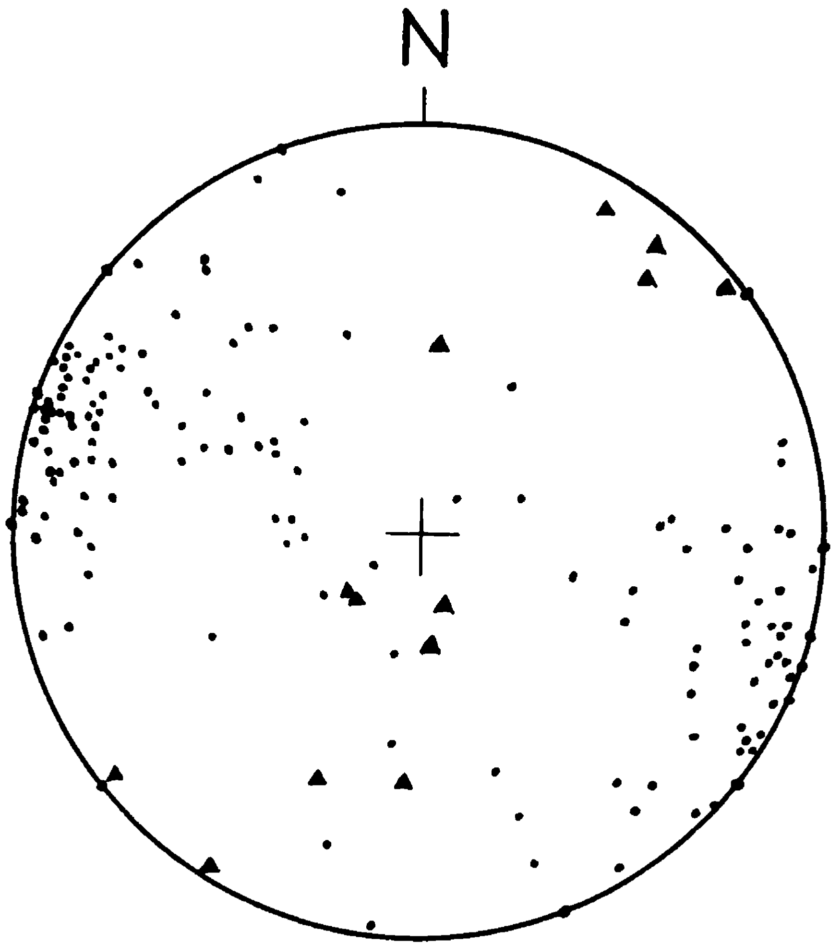

Fig. 18.--Stereographic plot of striations. Triangles indicate a separate generation, differentiated only where shear planes lie in close proximity to each other, so that it may be observed that the striations can not be reconciled by a single phase of deformation.

Hence, no definite conclusions can be made on the basis of them. They may lie in the a kinematic axis (normal to the fold axis) of the northwest-trending folding.

Far more dominant striations produce a possible vertical great circle girdle in a N 70° W orientation. Although shear plane orientations were not carefully recorded, it seemed apparent to the author that these shear planes are in agreement with the vertical great circle interpretation. The interpretation may be complicated by inclusion of a few striations related to folding about the steeply-plunging axis. However, the strong spread along a nearly horizontal girdle is not thought to be genetically related to the steep-axis folding. Nor did it seem apparent to the author that these striations underwent rotation about the steeply-plunging axis.

In any case, all of these striations cannot be reconciled with any fold event evident in the project area; therefore, it is necessary to appeal to some other deformational event. In view of the previously stated observation of a relationship between easily separable surfaces which contain striations, and presence of reddish stain, it is suggested that striations formed at a very late stage, when rocks were somewhat brittle, and micas no longer subject to annealing of striations upon them. Planes of shear remained separated, such that ground water percolating along the shear planes resulted in weathering which produced the rusty stain.

The striations may be related to pushing during emplacement of stocks. One stock that is a possible candidate for this role is the shallowly intruded Lolo Hotsprings Batholith, which outcrops three miles to the northwest.

The abundance of striations in the southeast domain and paucity in the northwest domain may be due to concentration of shear stress by the inherent, effective roughness caused by pre-existing tightly-folded bedding in the southeast domain.

DISCUSSION AND CONCLUSIONS

A total of five deformational events or phases are evident in the Brushy Fork project area: 1) an earliest fold event, accompanying regional metamorphism, producing isoclinal, recumbent folds of uncertain axis orientation; 2) a second fold event (B), producing large, northwest-trending recumbent folds with complex cores, overturned to the northeast; 3) a phase of small significance in the project area (B'), probably related to and subsequent to the northwest folding, resulting in mesoscopic folds and crenulations plunging in about the same direction, but at a steeper angle than major northwest folds; 4) folding about a steeply-plunging axis (B''), probably associated with regional strike-slip faulting; and 5) an event of uncertain heritage which produced striations in a N 70° W vertical great circle orientation.

All the workers in nearby areas (Langton, 1935; Hall, 1968; Anderson, 1959; Chase, 1961, 1968; Nold, 1968; and Wehrenberg, 1967) indicate, or may be reconciled with, an early isoclinal folding accompanying metamorphism, and northwest folding followed by strike-slip faulting. Structures in the Brushy Fork area are directly correlatable to these events. The workers also indicate other deformational events and periods of intrusion which are not observed in the project area. Correlations which the author believes reasonable amongst several of the workers appear in figure 19.

Reconstruction of structure as it existed prior to rotation about the steeply-plunging axis requires not only rotation of orientation, but also major rotation in space. Such an attempt is crude, and necessarily highly qualitative. Several attempts were made, with lateral rotation in space estimated from the fold trend sub-domain map (Fig. 3, p. 12), swinging fold trends into northwest alignment about hinges at the sub-domain boundaries. Although no concrete picture can be presented, such manipulations combined with appropriate cross-sections from them give the author the distinct impression that the northwest folds have the form of figure 20. This northeast-southwest vertical cross section of the northwest folds prior to steep-axis folding shows a large, recumbent, flexural-slip or possibly flexural-flow fold. The strongly deformed rocks characteristic of the southeast domain are in the

<table>
<tr><th></th><th>Nold, 1968b</th><th>Present study</th><th>Chase, 1968</th></tr>
<tr><td>EARLY</td><td>Similar-style (?) folding with axial plane schistosity</td><td>Isoclinal folding during metamorphism</td><td>Similar-style folds with penetrative schistosity, high amplitude/wave length</td></tr>
<tr><td></td><td>Southwest-trending similar-style folding; bends schistosity</td><td></td><td>Flexural-slip folding now plunging steeply to southwest</td></tr>
<tr><td></td><td>Northwest-trending similar-style folding; bends schistosity</td><td>Northwest trending folds with complex cores; overturned to northeast</td><td>Flexural-slip folding with steep, northwest-trending axial plane</td></tr>
<tr><td></td><td>Steep-axis open folding bending schistosity, possibly concurrent with igneous intrusion</td><td rowspan="3">Steep axis,flexural-slip folds, possibly related to strike-slip faulting

Brittle deformation--pushing in WNW-ESE orientation</td><td>Macroscopic, small circle rotation about steep axis; possibly due to forceful batholithic intrusion</td></tr>
<tr><td rowspan="2">LATE</td><td>East-west-trending faults, offset by north-south-trending faults</td><td rowspan="2">Granulation during anticlinal folding and diapiric uplift</td></tr>
<tr><td>High-angle northeast- to north-south-trending faults</td></tr>
</table>

Fig. 19.--Correlation of deformations found in the present study with those indicated by Nold (1968b) and Chase (1968) from nearby localities.

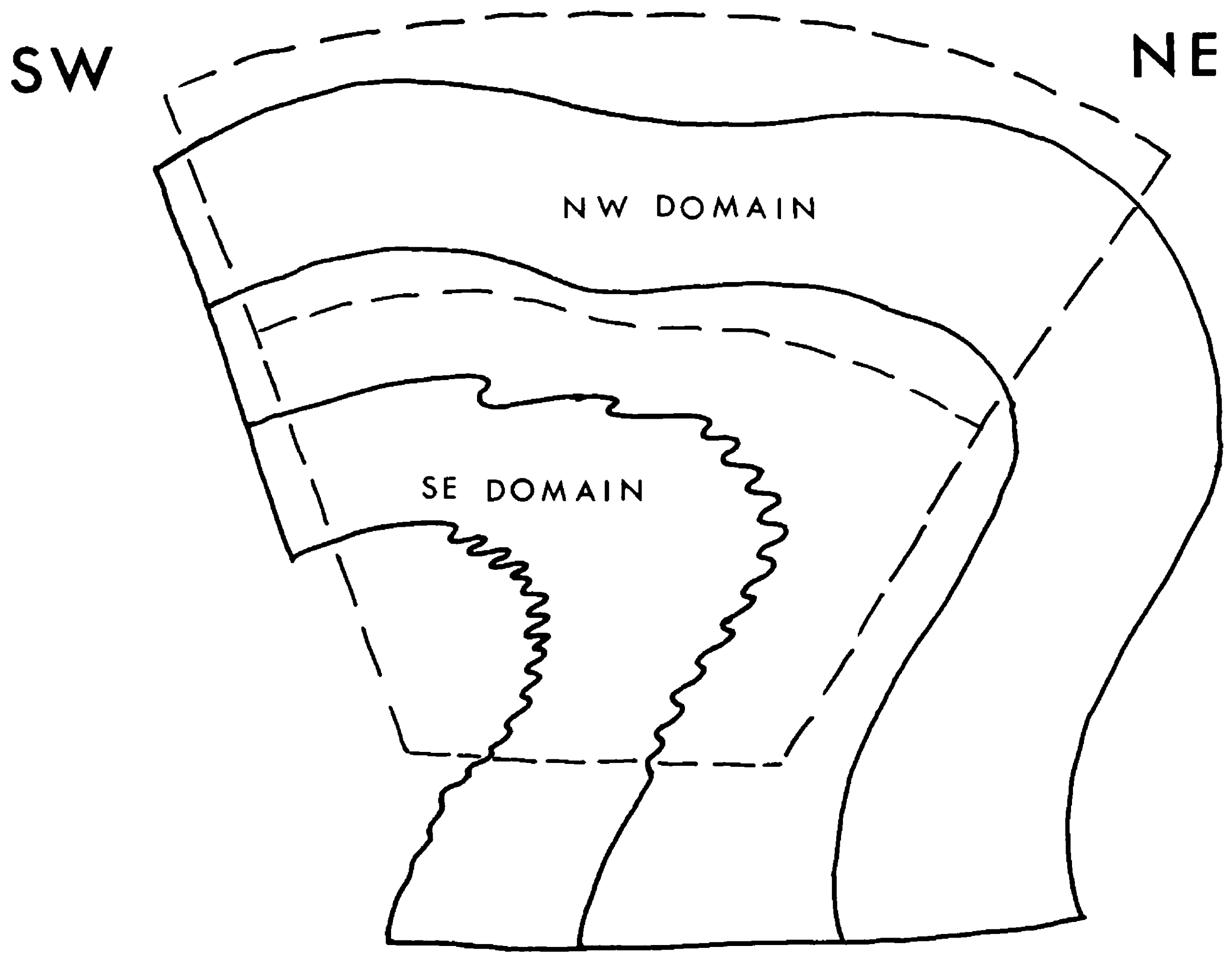

Fig. 20.--Southwest-northeast vertical schematic cross-section illustrating the form of the northwest-trending folds prior to steep-axis folding, and the relationship between the northwest and the southeast domains. About one mile across fold.

core of the northwest-trending fold, a zone of intensified compressive stress. Farther from the core, deformation was less intense, creating the gently deformed bedding of the northwest domain.

Three possibly significant contributions to an understanding of the geology of the area made by this study are:

1. Intensely folded, pegmatitic zones may be found associated with the cores of northwest folds.
2. Strike-slip movement may produce folding about a steeply-plunging axis in areas of pre-existing steeply-dipping beds, rotating earlier structures through a large arc, and resulting in considerable confusion of structure.
3. Striations are associated with a late structural event in the area, perhaps pushing in a N 70^{o} W-S 70^{o} E direction.

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